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(54) **MAGNETIC DEVICE WITH WEAKLY EXCHANGE COUPLED ANTIFERROMAGNETIC LAYER**

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(52) **U.S. Cl.**
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(58) **Field of Classification Search**
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See application file for complete search history.

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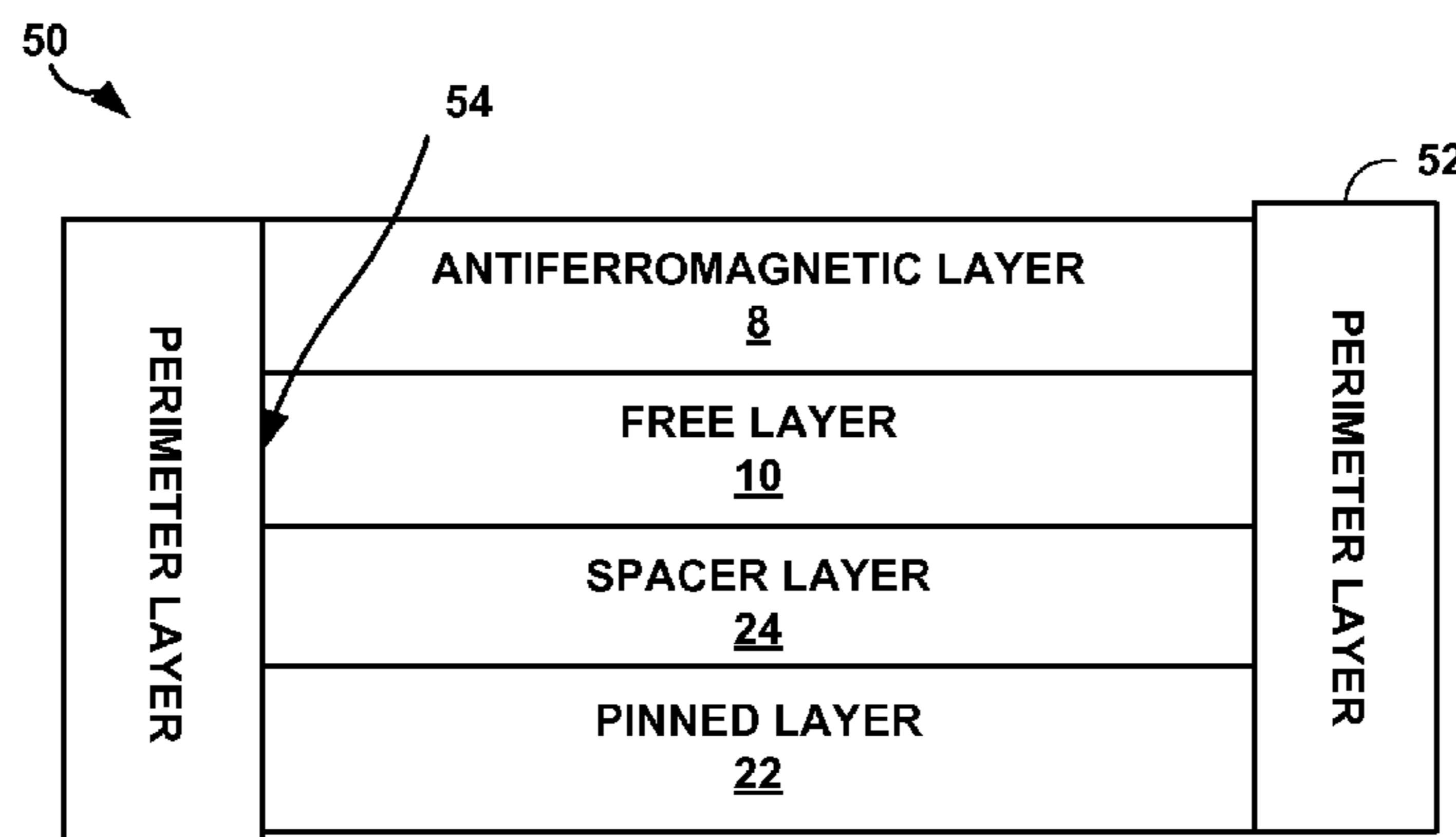
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(57) **ABSTRACT**

A magnetic device is provided in one example that comprises a free layer having a magnetic anisotropy. The magnetic anisotropy is at least partially non-uniform. The magnetic device further comprises an antiferromagnetic layer adjacent to and weakly exchange coupled with the free layer, wherein the weak exchange coupling reduces the non-uniformity of the magnetic anisotropy of the free layer.

20 Claims, 4 Drawing Sheets



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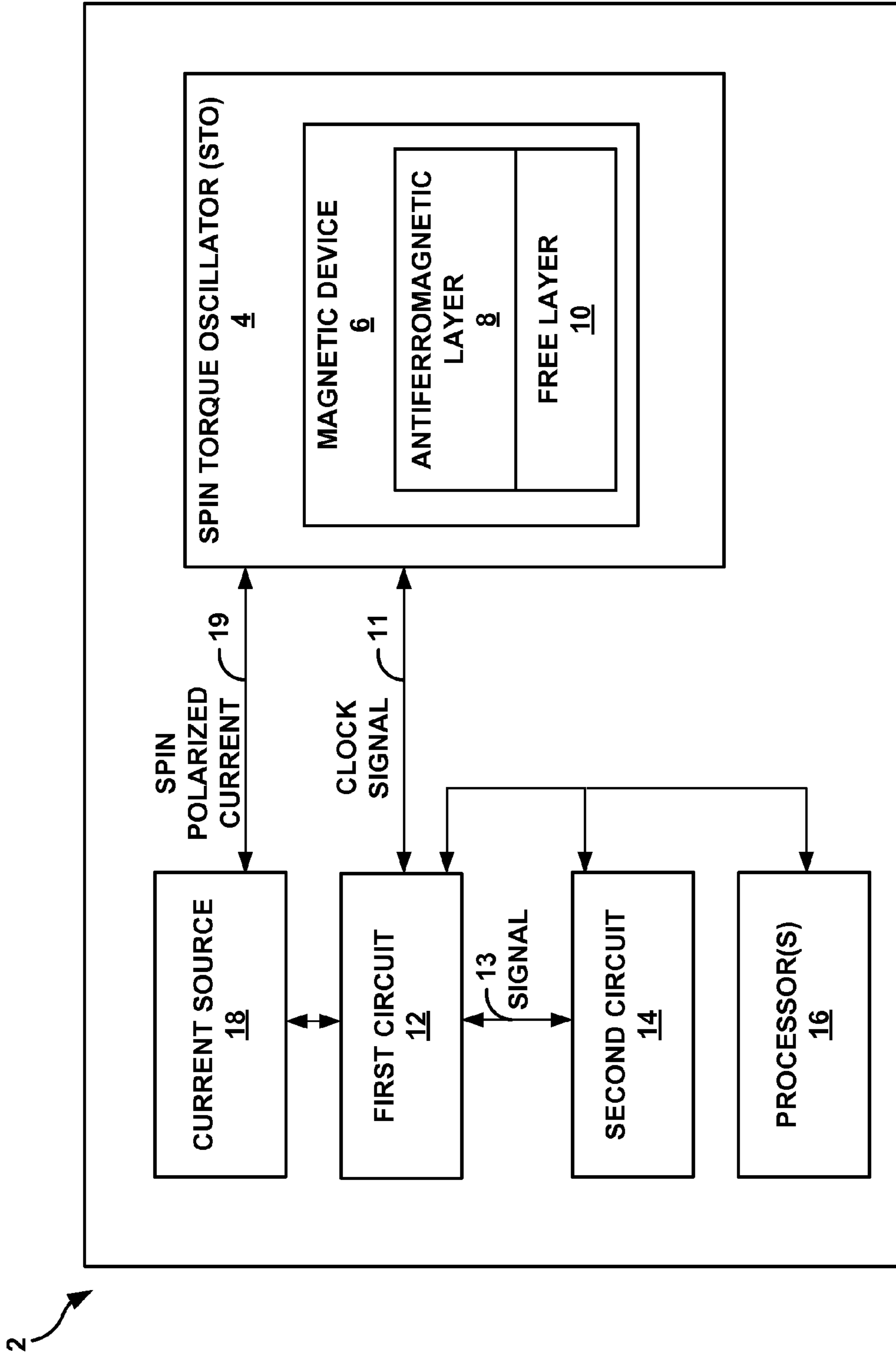


FIG. 1

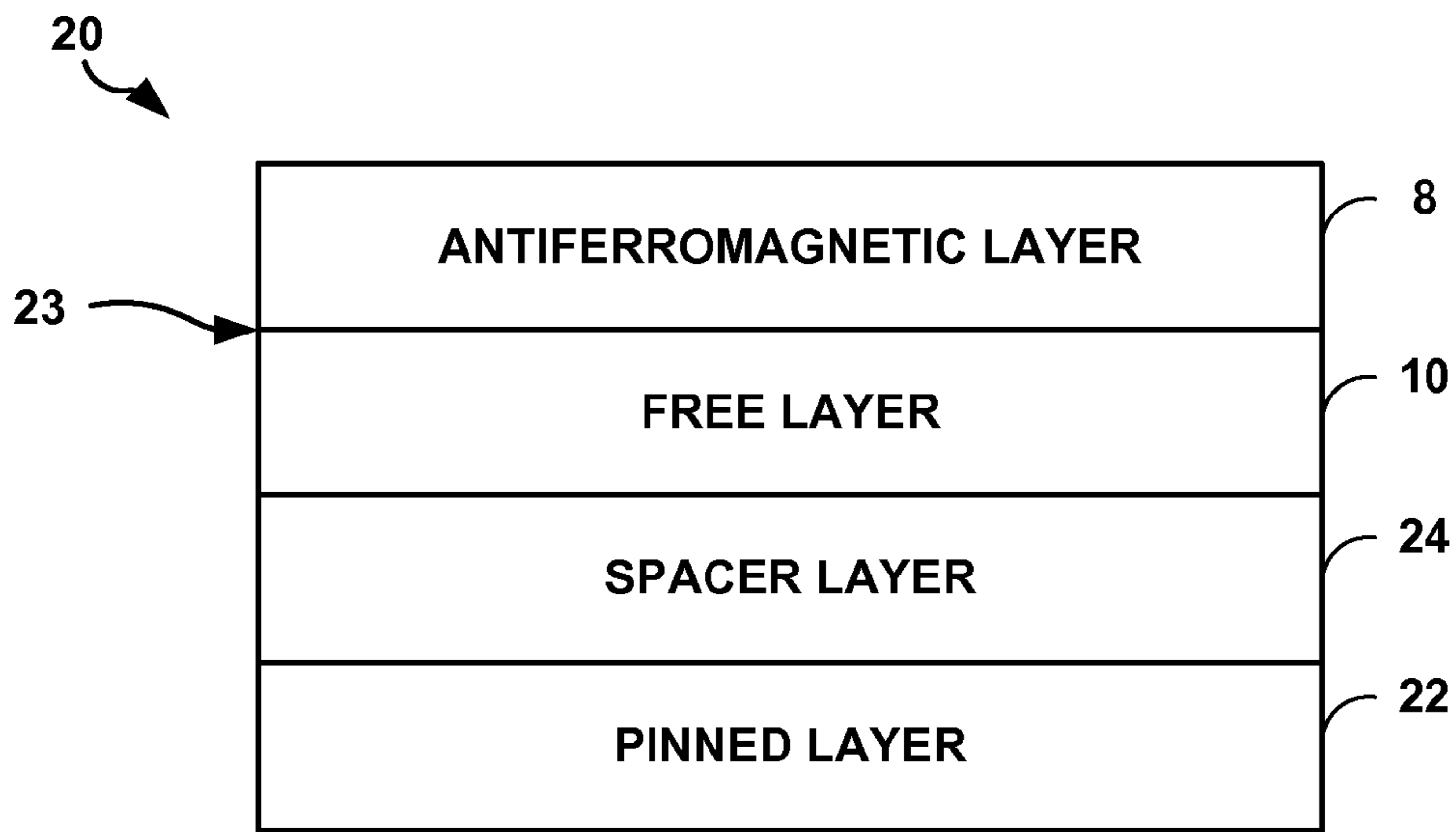


FIG. 2A

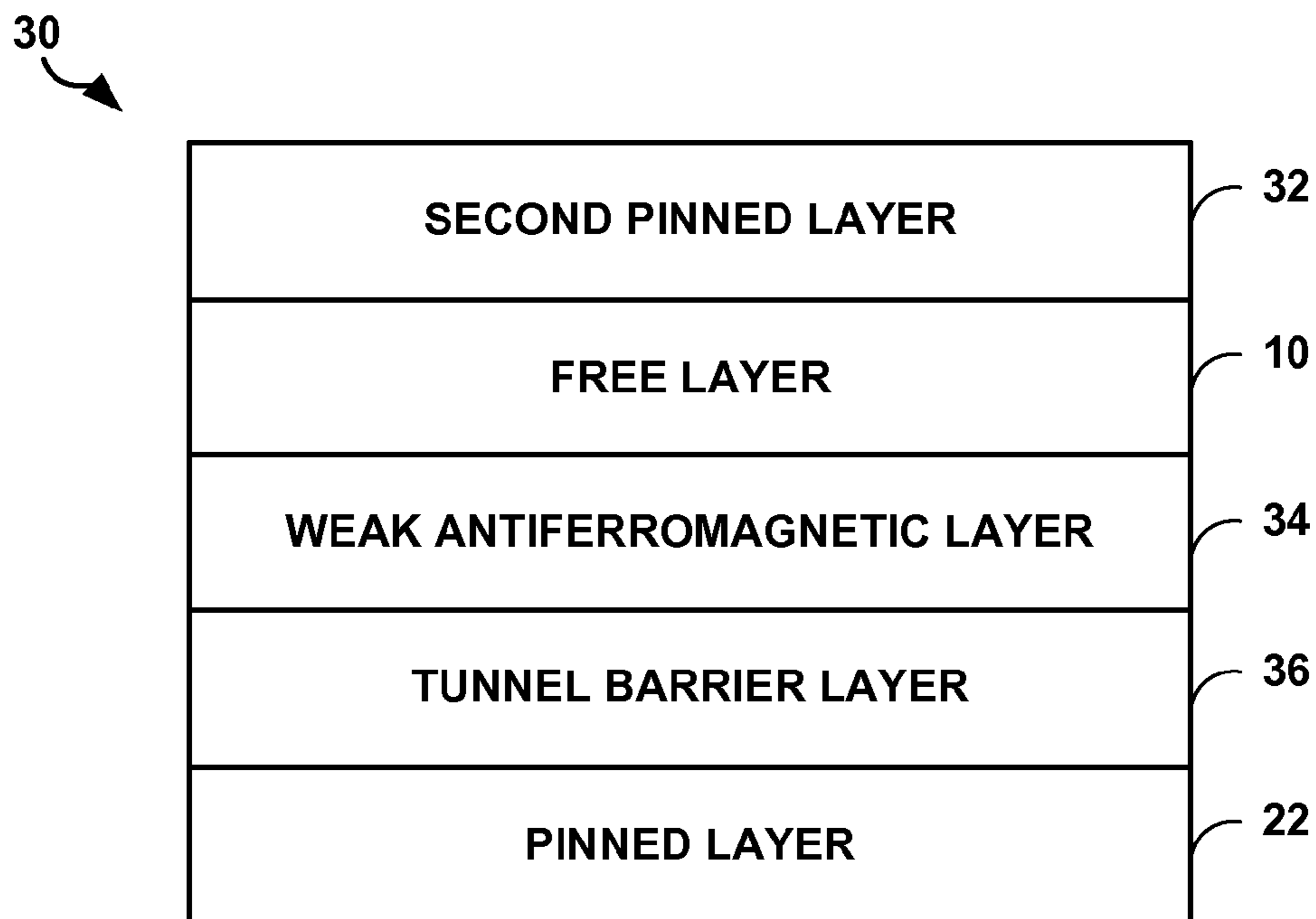


FIG. 2B

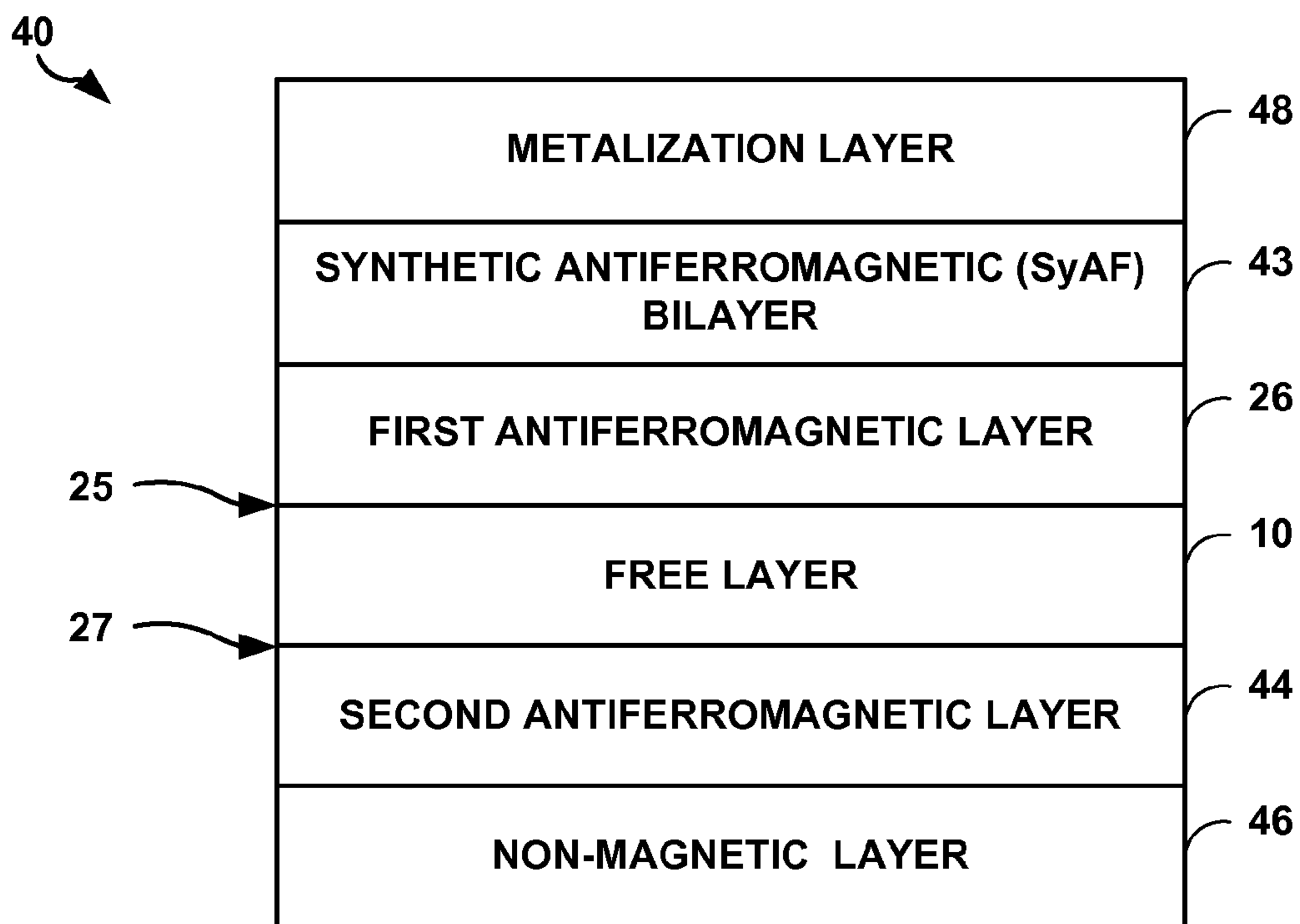


FIG. 2C

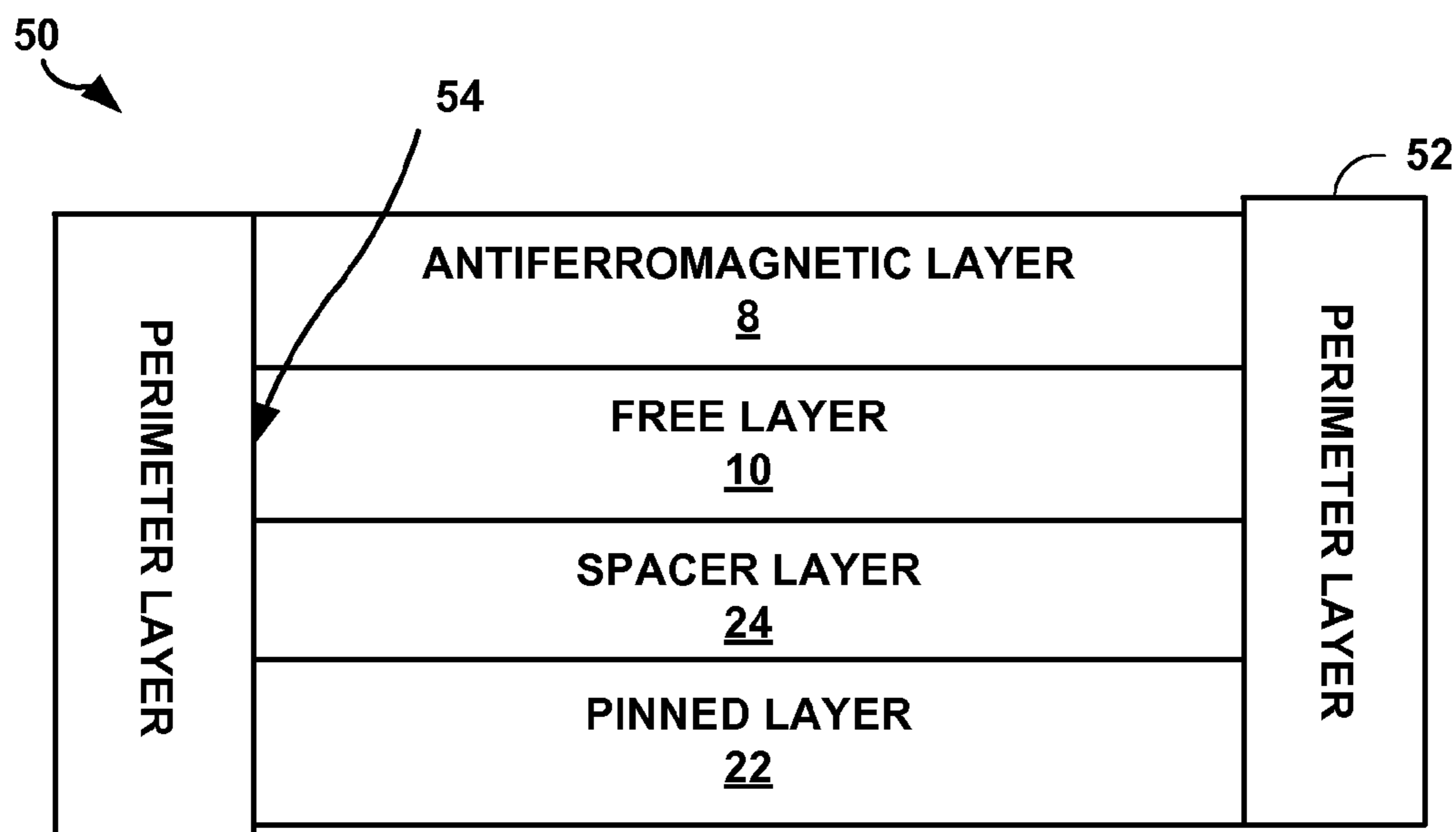
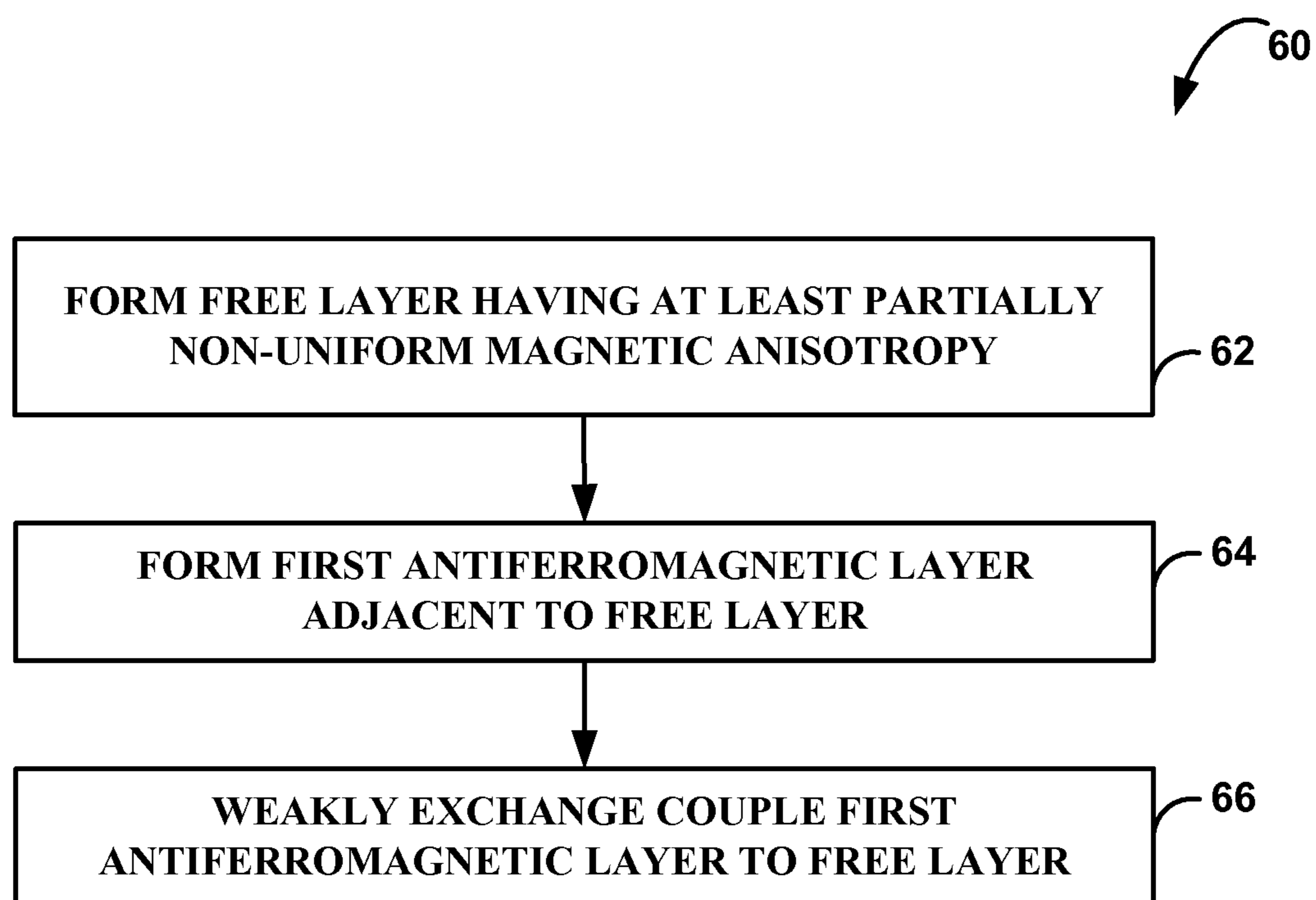


FIG. 2D

**FIG. 3**

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MAGNETIC DEVICE WITH WEAKLY EXCHANGE COUPLED ANTIFERROMAGNETIC LAYER

TECHNICAL FIELD

The disclosure relates to magnetic devices, such as magnetic devices that may be used in spin torque oscillators.

BACKGROUND

Some spin torque oscillators (STOs) may detect the presence and strength of a magnetic field due to changes in a magnetic oscillation of the STO that is induced in a free layer by a spin torque of the magnetic field.

SUMMARY

In one example, a magnetic device is provided that comprises a free layer having a magnetic anisotropy, wherein the magnetic anisotropy is at least partially non-uniform. The magnetic device further comprises an antiferromagnetic layer adjacent to and weakly exchange coupled with the free layer, wherein the weak exchange coupling reduces the non-uniformity of the magnetic anisotropy of the free layer.

In another example, a method for manufacturing a magnetic device is provided. The method may comprise forming a free layer having at least a partially non-uniform magnetic anisotropy and forming an antiferromagnetic layer adjacent to the free layer, wherein the antiferromagnetic layer reduces the non-uniformity of the magnetic anisotropy.

According to another example, a system is provided that comprises a circuit and a spin torque oscillator coupled to the circuit. The spin torque oscillator may comprise a free layer having at least a partially non-uniform magnetic anisotropy. The spin torque oscillator may further comprise at least one antiferromagnetic layer weakly exchange coupled to the free layer, wherein the weak exchange coupling causes the antiferromagnetic layer to reduce the non-uniformity of the magnetic anisotropy. A current may induce a magnetic field in the free layer, and the spin torque oscillator provides a signal related to the magnetic field to the circuit.

The details of one or more examples of the disclosure are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the disclosure will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is a block diagram illustrating one example of a device comprising a spin torque oscillator including a magnetic device comprising at least one antiferromagnetic layer weakly exchange coupled to a free layer.

FIGS. 2A-2D are block diagrams illustrating example magnetic devices including at least one antiferromagnetic layer weakly exchange coupled to a free layer.

FIG. 3 is a flowchart illustrating an example method for manufacturing a magnetic device including at least one antiferromagnetic layer weakly exchange coupled to a free layer.

In accordance with common practice, the various described features are not drawn to scale and are drawn to emphasize features relevant to the present disclosure. Like reference characters denote like elements throughout the figures and text.

DETAILED DESCRIPTION

In some magnetic devices, the introduction of current through the device causes magnetic moments in a free layer to

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reverse, such that the magnetization of the free layer oscillates. This reversal of magnetic moments may be referred to as spin precession. Spin precession of the free layer can generate power, which can be used for various purposes, such as to support relatively high bandwidth wireless communication. Uneven precession of the free layer can reduce the power output of the magnetic device. Example magnetic devices described herein include at least one antiferromagnetic layer that may help improve the uniformity of the precession of the free layer, which may help increase power output of the magnetic devices. The antiferromagnetic layer can be positioned adjacent to the free layer, such as above, below, or along an outer perimeter of the free layer, and, as described below, is weakly exchange coupled to the free layer. The presence of the antiferromagnetic layer can improve the uniformity of the magnetization of the free layer, which supports a more uniform precession. In this way, the antiferromagnetic layer may cause the spin precession of the free layer to be more even and steady compared to examples in which the magnetic device does not include the weakly exchange coupled antiferromagnetic layer.

Spin torque oscillators can be subject to errors, including timing jitter and phase noise with respect to induced and desired spin-precession response. These errors may result from edge pinning effects in the free layer of the STO. The timing jitter indicates cycle-to-cycle time lags and variability in the oscillation of the magnetization. This variability can degrade the desired oscillation performance and power transfer characteristics. These errors and non-uniformities may decrease the reliability and accuracy of the STO.

In addition to increasing the power output of the magnetic device, an improvement in the uniformity in the spin precession of the free layer can reduce phase noise. The phase noise may result from different atoms of the free layer rotating magnetic moments out of synch. For example, some atoms of the free layer may lead the rotation of magnetic moment, while other atoms may lag. The introduction of the at least one antiferromagnetic layer that is weakly exchange coupled to the free layer may help the atoms of the free layer rotate in synch, such that the rate of precession of the free layer is more constant. In addition, increasing the uniformity of spin precession of the free layer may also reduce timing jitter. In some examples, a reduction in timing jitter and phase noise may be achieved by defining the material structure and geometry of the magnetic device to support a single, dominant magnetization-reversal and precessional mode.

In some examples, the uniformity of precession of the free layer is improved through the definition of an easy-axis canting in the free layer. For example, a bias (easy-axis canting) is defined, for example, for an in-plane structure or for a perpendicular structure (e.g., a free layer) of the magnetic device. This easy-axis canting can help improve coherent precession and magnetization swing of the structure with more uniform anisotropy and weakly exchange coupling the free layer to an antiferromagnetic layer than in magnetic devices without an antiferromagnetic layer weakly exchange coupled to a free layer. In some examples, the magnetic device includes a circular, elliptical, or cylindrical geometry, which may reduce demagnetization. In addition, in some examples, the magnetic device includes a perimeter layer positioned around an outer perimeter of the device, which may help reduce pinning and coupling at the periphery of the device to reduce the likelihood or strength of secondary precession modes.

FIG. 1 is a block diagram illustrating one example of a system 2 comprising a spin torque oscillator (STO) 4 including a magnetic device 6 comprising at least one antiferromagnetic layer 8 weakly exchange coupled to a free layer 10.

System 2 may further include a first circuit 12, a second circuit 14, and one or more processors 16, and a current source 18. In some examples, system 2 may be one or more devices. Examples of system 2 may include any computing device (e.g., a desktop personal computer (PC), a mobile device, a tablet PC, and the like), a wireless device (e.g., a cell phone, radio, and the like), a satellite communications device, a radar device, as well as any other device or system where STO 4 may be utilized.

Spin torque oscillator 4 may detect the presence of a magnetic field via magnetic device 6. Magnetic device 6 may detect a magnetic field through a change in precessional oscillation frequency of a magnetization of free layer 10. In some examples, magnetic device 6 may be a magnetoresistive sensor, including at least one of a giant magnetoresistive (GMR) device or a tunneling magnetoresistive (TMR) device. In other examples, magnetic device 6 may be any other type of magnetic device or sensor.

In one example, antiferromagnetic (AFM) layer 8 of magnetic device 6 is adjacent to free layer 10. As used herein, adjacent layers may refer to two layers at least partially, approximately physically contacting each other, such as directly adjacent to each other. AFM layer 8 may be composed of an antiferromagnetic material. Antiferromagnetic materials are materials in which the magnetic moments of atoms, ions, or molecules in the material tend to assume an ordered arrangement in the absence of an applied magnetic field. In some examples, antiferromagnetic layer 8 may be a weak antiferromagnetic layer.

In some examples, free layer 10 is composed of a material having low coercivity, such that free layer 10 may have an easily rotatable or moveable magnetic moment which responds to an external magnetic field (e.g., changes direction in the presence of). In some examples, free layer 10 may be composed of a ferromagnetic material having soft magnetization.

Free layer 10 may be a magnetic free layer having a magnetic anisotropy. A material with magnetic anisotropy may have magnetic properties that are directionally dependent. In one example, the magnetic anisotropy is approximately perpendicular to a biasing direction of free layer 10. A biasing direction may align a magnetic moment along a certain orientation. In other examples, the magnetic anisotropy of free layer 10 may be at another angle with respect to the biasing direction. In some examples, the magnetic anisotropy of free layer 10 is at least partially non-uniform. For example, there may be local variations in the magnetic anisotropy of free layer 10 due to the partially non-uniform magnetic anisotropy. In such an example, non-uniformity of the magnetic anisotropy may arise due to the proximity of other materials to free layer 10. For example, a pinned layer adjacent to free layer 10 may cause edge pinning effects in free layer 10, which can distort the magnetic anisotropy of free layer 10 along the surface proximate to the pinned layer.

In one example, antiferromagnetic layer 8 is weakly exchange coupled to free layer 10. Exchange coupling may result when a hard magnetization of an antiferromagnetic material causes a shift in a soft magnetization of a ferromagnetic material. For example, exchange coupling antiferromagnetic layer 8 to free layer 10 results in shifts in the magnetization of free layer 10 along an interface between antiferromagnetic layer 8 and free layer 10. In one example, weakly exchange coupling antiferromagnetic layer 8 to free layer 10 reduces non-uniformity of the anisotropy in free layer 10, such as by reducing the dispersion effects of the magnetization of free layer 10. The exchange coupling between antiferromagnetic layer 8 and free layer 10 is

selected to be relatively weak, such that the anisotropy of free layer 10 is maintained. In another example, weakly exchange coupling antiferromagnetic layer 8 to free layer 10 improves the non-uniformity of the anisotropy in free layer 10. Any two layers described herein as being weakly exchange coupled are weakly exchange coupled similar to antiferromagnetic layer 8 and free layer 10.

A weak exchange bias due to the weak exchange coupling may be present at an interface between antiferromagnetic layer 8 and free layer 10. For example, non-uniformity of the magnetic anisotropy of free layer 10 may result in a hysteresis loop of free layer 10 having some local variations, non-linearity, or asymmetries. In such an example, the weak exchange coupling may reduce the non-uniformity of the magnetic anisotropy, resulting in a smoother hysteresis loop, without significantly shifting the hysteresis loop. In another example, the weak exchange bias may affect the magnetic anisotropy of free layer 10. In one example, the weak exchange coupling does not significantly reduce the effects of thermal energy on the anisotropy/or hysteresis switching of free layer 10. In another example, the weak exchange coupling does not induce magnetic anisotropy in free layer 10. In a further example, the weak exchange coupling between AFM layer 8 and free layer 10 may not substantially change the anisotropy of free layer 10. The antiferromagnetic properties of AFM layer 8 can be selected to achieve any of these results of the weak exchange coupling.

In one example, a hysteresis loop in a switching field of free layer 10 may not be significantly altered by the weak exchange coupling. In one example, the weak exchange coupling may shift an antiferromagnetic exchange field (H_{ex}) by anywhere between approximately -1 to 1 Oersted (Oe). In another example, the weak exchange coupling may shift H_{ex} anywhere between approximately -5 to 5 Oe. In another example, the hysteresis loop is centered around approximately 0 Oe. In other examples, the hysteresis loop is centered around other magnetic field strength values. In one example, the weak exchange coupling between antiferromagnetic layer 8 and free layer 10 may not result in pinning any interfacial spins of free layer 10. In some examples, the canting angle may be as large as possible without switching the magnetization.

Current source 18 may provide a current to STO 4. Current source 18 may be a battery or any other current source. In one example, the current that is applied to magnetic device 6 is a spin polarized current 19. STO 4 detects magnetization induced by spin polarized current 19 by using magneto-resistance and magneto-resistive current effects. In one example, spin polarized current 19 is not spin polarized until the current from current source 18 is applied to a layer in magnetic device 6. In one example, spin polarized current 19 may drive a precession of a magnetization in free layer 10. The amount of spin polarized current 19 may be selected to compensate for any energy lost in the precession. In another example, the direction of spin polarized current 19 may be selected to influence the direction of the precession of the magnetization in the free layer 10.

The effects of weakly exchange coupling AFM layer 8 with free layer 10 results in improved precession of the magnetization of free layer 10 in the presence of spin polarized current 19, which can subsequently improve communications in such implementations. In one example, STO 4 may assist in chip-to-chip communications in system 2, for example, between first circuit 12 and second circuit 14. As used herein, "chip-to-chip" may refer to any implementation where a number of devices or components within a device are electrically coupled together. Examples of a device may include any

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circuit, such as first circuit **12** and second circuit **14**, chip, memory, processor, micro-controller, video card, or the like. In some examples, system **2** employs at least one high rate device, for example, with an operating frequency measured in giga-Hertz (GHz) or higher.

STO **4** may be a local oscillator for first circuit **12**. In one example, STO **4** may output a signal related to the detected magnetic field to first circuit **12**. In one example, the signal related to the detected magnetic field is a clock signal **11**. First circuit **12** may transfer a signal **13** to second circuit **14**, where clock signal **11** is used as a carrier frequency for signal **13**. In one example, the weak exchange coupling between antiferromagnetic layer **8** and free layer **10** improves the consistency and reliability of clock signal **11**. In one example, clock signal **11** may have a narrow bandwidth, low jitter, and good phase noise properties. In some examples, clock signal **11** may have a bandwidth up to approximately 100 Megahertz (MHz). In one example, clock signal **11** has a bandwidth between approximately 100 kilohertz (kHz) to approximately 100 MHz. Using STO **4** for clocking may eliminate the need to have a local oscillator (LO) circuit coupled to first circuit **12**.

In other examples, system **2** may include additional circuitry. For example, system **2** may include more than one spin torque oscillator **4**. For example, system **2** can include a second STO that is coupled to second circuit **14** and used to decode the carrier frequency. In some examples, STO **4** is a spin torque nano-oscillator (STNO). The example of system **2** shown in FIG. **1** is merely one example of a system that can include magnetic device **6** that includes AFM layer **8** weakly exchange coupled to free layer **10**. For example, in another example of a system that includes magnetic device **6**, current source **18** is located external to system **2**.

FIGS. **2A-2D** are block diagrams illustrating example magnetic devices including at least one antiferromagnetic layer weakly exchange coupled to a free layer. Schematic cross-sectional views of the magnetic devices are depicted in FIGS. **2A-2D**. The magnetic devices may have any suitable shape. FIG. **2A** depicts one example of a magnetic device **20** which may comprise an antiferromagnetic layer **8** weakly exchange coupled to a free layer **10** along an interface **23** between layers **8**, **10**. Because antiferromagnetic layer **8** may be weakly exchange coupled to free layer **10**, the magnetic anisotropy in free layer **10** is more uniform compared to magnetic devices that do not include an AFM layer **8** or an AFM layer **8** weakly exchange coupled to free layer **10**. In one example, edge pinning effects on free layer **10** are reduced along interface **23** due to the weak exchange coupling with AFM layer **8**. The reduction of the edge pinning effects on free layer **10** may enable free layer **10** to precess more freely, which may help increase the uniformity of the precession of free layer **10**.

In one example, an easy-axis is defined which may be canted to support uniform magnetization and coherent reversal and precession for in-plane or perpendicular magnetization. In one example, a magnetization in free layer **10** is canted, either out of the plane or rotated in the plane of the free layer **10**, or any angle between. In another example, a canted easy-axis may be defined in a pinned layer. In one example, the weak AFM coupling may be applied to any orientation of the magnetization.

In one example, free layer **10** may be a permalloy, that is, composed at least partially of nickel-iron (NiFe). For example, free layer **10** may be approximately 80% Ni and 20% Fe. Additional examples of free layer **10** may be composed of other NiFe compositions or of other suitable mate-

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rials. In one example, free layer **10** may be approximately 1 to 5 nanometers (nm) thick. In other examples, free layer **10** may be other thicknesses.

Examples of antiferromagnetic layer **8** may be composed of manganese (Mn), platinum manganese (PtMn), iridium manganese (IrMn), nickel manganese (NiMn), iron manganese (FeMn), palladium platinum manganese (PdPtMn), or combinations thereof. In other examples, AFM layer **8** may be composed of other materials. In some examples, AFM layer **8** may be approximately 1 to 5 nm thick. In other examples, AFM layer **8** may be other thicknesses.

Magnetic device **20** may further comprise a pinned layer **22**. Pinned layer **22** may be a reference layer having an approximately fixed magnetic moment. Examples of pinned layer **22** may be composed of at least one of nickel-iron (NiFe), nickel-iron alloys, iron cobalt (FeCo), nickel iron cobalt (NiFeCo), or combinations thereof. Other suitable materials can also be used for pinned layer **22**. In some examples, the magnetization of free layer **10** is biased with respect to the fixed magnetic field of pinned layer **22**. Magnetically biasing free layer **10** enables the magnetization of free layer **10** to precess due to spin torque oscillation. Pinned layer **22** can have a greater thickness than free layer **10** in some examples. In one example, pinned layer **22** may be approximately 1 to 20 nm thick, such as approximately 3 to 20 nm thick. In other examples, pinned layer **22** may be other thicknesses. In some examples, the thickness of pinned layer **22** may be selected for the strength of the switching field; a thicker pinned layer **22** leads to a greater switching field.

In the example of FIG. **2A**, free layer **10** is located between antiferromagnetic layer **8** and pinned layer **22**. That is, antiferromagnetic layer **8** may be located on a first side of free layer **10** and pinned layer **22** may be located on a second side of free layer **10** opposite the first side. In one example, antiferromagnetic layer **8** may be kept relatively far from pinned layer **22** within the magnetic device **20**, e.g., relative to free layer **10**, in order to help reduce the possibility that antiferromagnetic layer **8** will be coupled to pinned layer **22**. In one example, the fixed magnetic moment of pinned layer **22** is further stabilized by another antiferromagnetic layer.

In some examples, magnetic device **20** may also comprise a spacer layer **24** formed over the pinned layer **22**. One example of spacer layer **24** may be a non-magnetic spacer layer. One example of a non-magnetic spacer layer **24** may be an electrically conductive spacer layer when magnetic system **20** is a giant magnetoresistive (GMR) sensor. As another example, spacer layer **24** may be a non-magnetic, electrically insulating barrier layer when the source of magnetoresistance of magnetic system **20** is based on a tunneling magnetoresistive (TMR) effect. In one example, spacer layer **24** may be approximately 1 nm thick. In other examples, spacer layer **24** may be other thicknesses.

FIG. **2B** depicts one example of a tunneling magnetoresistive (TMR) device **30**. TMR device **30** may comprise a tunnel barrier layer **36** and an antiferromagnetic layer **8** weakly exchange coupled to a free layer **10**. TMR device **30** may further include a second pinned layer **32** in addition to pinned layer **22**. Tunnel barrier layer **36** may provide TMR functionality to TMR device **30**. In one example, tunnel barrier layer **36** may be one of aluminum oxide (AlOx) or magnesium oxide (MgOx), or any other suitable material.

In one example, pinned layer **22** and second pinned layer **32** may have opposite magnetization and are placed on opposite sides of free layer **10** to supply spin-polarized currents of the desired polarity. The inclusion of two pinned layers having substantially opposite magnetization can help control the precession direction of free layer **10**. In some examples,

pinned layer **22** and second pinned layer **32** may be located either adjacent to or some distance from the TMR device **30**.

FIG. 2C is a block diagram of one example of a giant magnetoresistive (GMR) device **40**. In this example, GMR device **40** may have a first antiferromagnetic layer **26** and a second antiferromagnetic layer **44**. First antiferromagnetic layer **26** may be weakly exchange coupled to a first side **25** of free layer **10**. Second antiferromagnetic layer **44** may be weakly exchange coupled to a second side **27** of free layer **10**. In this example, first side **25** is opposite second side **27**. Both antiferromagnetic layers **26** and **44** improve the uniformity of the magnetic anisotropy of free layer **10**. Positioning an AFM layer **26** or **44** on the top or bottom of free layer **10** results in exchange coupling through horizontal surfaces **25** or **27**, respectively. The addition of weak AFM exchange coupled layers **26** and **44** to free layer **10** may reduce dispersion effects to the magnetization of free layer **10**. Because spins are throughout free layer **10**, including along sides **25** and **27**, any precession may be influenced by defects in the spins along the sides of free layer **10**. Having an antiferromagnetic layer **26** or **44** on both sides **25** and **27** of free layer **10** further regulates the precession to improve its uniformity.

GMR device **40** may include a non-magnetic layer **46** as a spacer layer. In some examples, non-magnetic layer **46** may be made of copper (Cu), or the like. Another example of non-magnetic layer **46** may be a non-magnetic, electrically insulating barrier layer. Non-magnetic layer **46** may provide giant magnetoresistive functionality to GMR device **40**.

GMR device **40** may also include a synthetic antiferromagnetic (SyAF) bilayer **43** as a pinned layer. In one example, a current is applied to SyAF bilayer **43**. In one example, the current in SyAF bilayer **43** is spin polarized. GMR device **40** may further include a metalization layer **48** that may be a capping layer formed over the sensor stack of GMR device **40**. One example of metallization layer **48** may be tantalum (Ta), although any material suitable for capping may be used.

FIG. 2D is a block diagram of an example of a magnetic sensor **50**. As described herein, magnetic sensor **50** has the same structure as magnetic device **20** (FIG. 2A), with the addition of a perimeter layer **52**. Perimeter layer **52** is positioned adjacent to at least one of free layer **10** or pinned layer **22** to suppress edge pinning effects. In the example shown in FIG. 2D, perimeter layer **52** is formed at least partially along an outer perimeter **54** of free layer **10**. In examples in which magnetic sensor **50** is shaped as an elliptical or circular device, layers **8**, **10**, **22**, and **24** may be layers having an approximately elliptical or circular cross-sectional shape in a plane that is substantially perpendicular to the plane of the image shown in FIG. 2D. Perimeter layer **52** may be formed around some or all of layers **8**, **10**, **22**, and **24**. In one example, perimeter layer **52** is formed only around the outer perimeter **54** of free layer **10**. Perimeter layer **52** further improves the uniformity of precession of a magnetization of free layer **10**.

In one example, perimeter layer **52** may be an antiferromagnetic material. AFM perimeter layer **52** may be weakly exchanged coupled to at least free layer **10**. In such an example, AFM perimeter layer **52** reduces edge pinning effects along perimeter **54** of free layer **10**.

In another example, perimeter layer **52** may be a soft layer. A soft perimeter layer **52** may be a material that is highly permeable. When the magnetization of free layer **10** is canted, the magnetization may be influenced by magnetic poles forming on the edge(s) of free layer **10** as the magnetization precesses. The magnetic poles along perimeter **54** of free layer **10** can cause a non-uniform demagnetization field. Soft perimeter layer **52** may draw in any magnetization from these surface poles because of the permeability of the soft layer.

Likewise, soft perimeter layer **52** may not emit a stray magnetic field. This may allow material properties to dominate the precession of the magnetization so it is more uniform.

In another example, perimeter layer **52** may be a decoupling or non-pinning layer. The decoupling or non-pinning layer may make the stoichiometry (chemical composition) of materials in contact with it more uniform. For example, during deposition, the composition of the deposited materials may differ between the edges and the bulk of the material. The decoupling or non-pinning layer can improve the uniformity of these layers by homogenizing the chemical composition of the material. For example, decoupling or non-pinning layer perimeter layer **52** may homogenize the stoichiometry of free layer **10** along perimeter **54**.

Any of the layers as described herein with respect to FIGS. 2A-2D (such as pinned layer **22**, for example) may be a single layer or a structure of more than one layer or partial layers. Furthermore, any of the layers or features described in any of the examples of FIGS. 2A-2D may be combined with each other for additional examples. Magnetic devices **20**, **30**, **40**, or **50** may also have additional layers or structures. For example, any of magnetic devices **20**, **30**, **40**, or **50** may include a magnetic shield layer. In such an example, a magnetic shield layer may be an electrically conductive, magnetic material, such as nickel-iron (NiFe). In further examples, the layers of the devices **20**, **30**, **40**, and **50** may be any type of structure, for example, polycrystalline, monocrystalline, amorphous, or the like.

FIG. 3 is a flowchart illustrating an example method **60** for manufacturing a magnetic device comprising at least one antiferromagnetic layer weakly exchange coupled to a free layer. Method **60** may include forming a free layer (e.g., free layer **10**) having at least partially non-uniform magnetic anisotropy (**62**). Method **60** may further include forming a first antiferromagnetic layer (e.g., antiferromagnetic layer **8**, antiferromagnetic layer **26**, antiferromagnetic layer **34**, or antiferromagnetic layer **44**) adjacent to the free layer (**64**). In such an example, the first AFM layer may reduce the at least partially non-uniformity of the magnetic anisotropy of the free layer.

Method **60** may further include weakly exchange coupling the first AFM layer to the free layer (**66**). In some examples, the first AFM layer may be weakly exchange coupled to the free layer based on the material properties of at least the first AFM layer, such that upon forming the first AFM layer adjacent to the free layer, the first AFM layer is weakly exchange coupled to the free layer. In other examples, the first AFM layer may be weakly exchange coupled to the free layer through performing a thermal anneal after deposition of the AFM layer. The temperature or duration of the thermal anneal may be selected to achieve a desired strength of the exchange coupling. Some examples of the temperature and duration of the thermal anneal may be between from approximately 100 to approximately 500 degrees Celsius ($^{\circ}$ C.) and the duration may be approximately 0.1 hours to 5 hours. In one example, the thermal anneal is performed for approximately 1 hour at approximately 250 $^{\circ}$ C. In other examples, alterations to the deposition process or configuration of the magnetic device may be made in order to achieve a weak exchange coupling of a desired strength.

In one example, method **60** may include forming a second antiferromagnetic layer adjacent to the free layer, wherein the second antiferromagnetic layer is located on a side of the free layer opposite the first antiferromagnetic layer. In other examples, method **60** may further include forming a perimeter layer at least partially around the free layer, wherein the perimeter layer further reduces the non-uniformity of the

magnetic anisotropy of the free layer. In yet another example, method 60 may include forming a pinned layer, wherein the free layer is located between first antiferromagnetic layer and the pinned layer.

Any method of deposition or fabrication now known or later developed may be used to implement method 60. For example, magnetic sputtering or molecular beam epitaxy (MBE) may be used to deposit the layers. Chemical or physical deposition methods may be used. In some examples, thin film deposition techniques are used to perform method 60.

Some existing spin torque oscillators are subject to timing jitter, phase noise, and sub-optimal or sub-maximum precession. Weakly exchange coupling an antiferromagnetic layer to a free layer reduces these effects and allows precession to be more uniform. In one example, the precession of magnetization in the free layer is increased. In another example, edge pinning effects are reduced by weakly exchange coupling one or more antiferromagnetic layers to the free layer. In one example, the weak AFM exchange coupling reduces noise effects due to temperature variation of magnetic device 6.

Examples of the present disclosure may reduce the power needed to run system 2. Further examples of the present disclosure may reduce the overall size of system 2 by increasing the power that is output by magnetic device 6. A magnetic device, according to examples of the present disclosure, may provide a higher frequency broad-frequency range tunable oscillator with low jitter, low phase noise, and high output power.

In the discussion and claims herein, the term “on” used with respect to two materials, one “on” the other, means at least some contact between the materials, while “over” means the materials are in proximity, but possibly with one or more additional intervening materials such that contact is possible but not required. Neither “on” nor “over” implies any directionality as used herein. The term “about,” “approximate,” or the like indicates that the value listed may be somewhat altered, as long as the alteration does not result in nonconformance of the process or structure to the illustrated example.

Terms of relative position as used in this disclosure are defined based on a plane parallel to the conventional plane or working surface of a wafer or substrate, regardless of the orientation of the wafer or substrate. The term “horizontal” or “lateral” as used in this disclosure is defined as a plane parallel to the conventional plane or working surface of a wafer or substrate, regardless of the orientation of the wafer or substrate. The term “vertical” refers to a direction perpendicular to the horizontal. Terms such as “on,” “side” (as in “sidewall”), “higher,” “lower,” “over,” “top,” and “under” are defined with respect to the conventional plane or working surface being on the top surface of the wafer or substrate, regardless of the orientation of the wafer or substrate.

Various aspects of the disclosure have been described. Aspects or features of examples described herein may be combined with any other aspect or feature described in another example. These and other examples are within the scope of the following claims.

The invention claimed is:

1. A system comprising:

a spin torque oscillator comprising a magnetic device, the magnetic device comprising:

a stack comprising a plurality of layers including a free layer having a magnetic anisotropy, wherein the magnetic anisotropy is at least partially non-uniform; and an antiferromagnetic layer formed at least partially around an outer perimeter of the stack and adjacent to the free layer and at least one other layer of the plu-

rality of layers of the stack, wherein the antiferromagnetic layer is weakly exchange coupled with the free layer, and wherein the weak exchange coupling of the antiferromagnetic layer reduces the non-uniformity of the magnetic anisotropy of the free layer.

2. The system of claim 1, wherein the antiferromagnetic layer comprises a first antiferromagnetic layer, the stack further comprising:

a second antiferromagnetic layer adjacent to and weakly exchanged coupled with the free layer, wherein the weak exchange coupling of the second antiferromagnetic layer further reduces the non-uniformity of the magnetic anisotropy of the free layer.

3. The system of claim 2, wherein the second antiferromagnetic layer is formed on a first side of the free layer, the stack further comprising:

a third antiferromagnetic layer adjacent to and weakly exchanged coupled with the free layer, wherein the weak exchange coupling of the third antiferromagnetic layer further reduces the non-uniformity of the magnetic anisotropy of the free layer, and wherein the third antiferromagnetic layer is formed on a second side of the free layer opposite the first side.

4. The system of claim 2, further comprising:

a pinned layer formed on a first side of the free layer, wherein the second antiferromagnetic layer is on a second side of the free layer opposite the first side.

5. The system of claim 2, wherein the stack defines a first edge and a second edge separated from the first edge in a first direction, the outer perimeter of the stack being defined at least in part by the first and second edges, and wherein the free layer and the second antiferromagnetic layer are stacked in a second direction that is substantially perpendicular to the first direction.

6. The system of claim 1, further comprising:

a soft layer formed at least partially around an outer perimeter of the free layer, wherein the soft layer further reduces the non-uniformity of the magnetic anisotropy of the free layer.

7. The system of claim 1, further comprising:

a decoupling layer formed at least partially around the outer perimeter of the stack and adjacent to the free layer, wherein the decoupling layer further reduces the non-uniformity of the magnetic anisotropy of the free layer.

8. The system of claim 1, wherein the antiferromagnetic layer comprises at least one of manganese (Mn), platinum manganese (PtMn), iridium manganese (IrMn), nickel manganese (NiMn), iron manganese (FeMn), palladium platinum manganese (PdPtMn), or combinations thereof.

9. The system of claim 1, further comprising:

a synthetic antiferromagnetic (SyAF) bilayer formed over the free layer, wherein a spin polarized current applied to the SyAF bilayer induces a magnetization in the free layer, wherein the magnetization processes at an approximately uniform rate.

10. The system of claim 1, wherein the free layer has a magnetization, wherein a direction of the magnetization is one of in a plane of the free layer, perpendicular to the plane of the free layer, or canted at any angle between in the plane and perpendicular to the plane.

11. The system of claim 1, wherein the magnetic device comprises at least one of a giant magnetoresistive (GMR) device or a tunneling magnetoresistive (TMR) device.

12. A method for manufacturing a magnetic device of a spin torque oscillator, the method comprising:

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forming a stack comprising a plurality of layers including a free layer having at least a partially non-uniform magnetic anisotropy; and

forming an antiferromagnetic layer at least partially around an outer perimeter of the stack and adjacent to the free layer and at least one other layer of the plurality of layers of the stack, wherein the antiferromagnetic layer reduces the non-uniformity of the magnetic anisotropy.

13. The method of claim **12**, wherein forming the antiferromagnetic layer comprises weakly exchange coupling the antiferromagnetic layer to the free layer, wherein the weak exchange coupling causes the antiferromagnetic layer to reduce the non-uniformity of the magnetic anisotropy.

14. The method of claim **13**, wherein weakly exchange coupling comprises performing a thermal anneal on the antiferromagnetic layer.

15. The method of claim **12**, wherein the antiferromagnetic layer comprises a first antiferromagnetic layer, and forming the stack further comprises:

forming a second antiferromagnetic layer adjacent to the free layer, wherein the second antiferromagnetic layer is weakly exchange coupled with the free layer and wherein the weak exchange coupling further reduces the non-uniformity of the magnetic anisotropy.

16. The method of claim **15**, wherein forming the stack further comprises:

forming a third antiferromagnetic layer adjacent to the free layer and on a side of the free layer opposite the second antiferromagnetic layer, wherein the third antiferromagnetic layer further reduces the non-uniformity of the magnetic anisotropy of the free layer.

17. The method of claim **15**, wherein forming the stack further comprises:

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forming a pinned layer, wherein the free layer is located between the second antiferromagnetic layer and the pinned layer.

18. A system comprising:

a circuit;

a spin torque oscillator coupled to the circuit, the spin torque oscillator comprising:

a stack comprising a plurality of layers including a free layer having at least a partially non-uniform magnetic anisotropy; and

an antiferromagnetic layer formed at least partially around an outer perimeter of the stack and adjacent to the free layer and at least one other layer of the plurality of layers of the stack, wherein the antiferromagnetic layer is weakly exchange coupled to the free layer, wherein the weak exchange coupling causes the antiferromagnetic layer to reduce the non-uniformity of the magnetic anisotropy;

wherein a current induces a magnetic field in the free layer, and wherein the spin torque oscillator provides a signal to the circuit, wherein the signal is related to the magnetic field.

19. The system of claim **18**, wherein the antiferromagnetic layer is a first antiferromagnetic layer, and the stack further comprises:

a second antiferromagnetic layer weakly exchange coupled to the free layer.

20. The system of claim **18**, wherein the circuit comprises a first circuit, wherein the signal related to the magnetic field is a clock signal, and wherein the first circuit uses the clock signal as a carrier frequency in a signal transfer to a second circuit.

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